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EFFECTS OF WIND-INDUCED DRIFT CURRENTS ON THE PROPAGATION OF SURFACE WAVES

Jin Wu

Hydronautics, Incorporated

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By

Jin Wu

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TABLE OF CONTENTS

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LIST OF FIGURES

ABSTRACT

Phase velocities were measured of dominant waves generated by wind and of simple progressive waves, generated mechanically, under wind. The results indicate that the wind-induced drift current has a significant effect on the phase velocity of short gravity waves. The effect varies inversely with wavelength and directly with fetch.

1. INTRODUCTION

The celerity of gravity waves of small amplitudes in either shallow or deep quiescent water has been well established (Lamb 1932). Accompanying wind-excited waves, there is also a drift current generated by the wind shear. Such currents possess characteristics of a boundary-layer type flow, having strong gradients near the air-water interface. Therefore, the influence of wind drift, with appreciable motion in only a shallow layer below the surface, is believed to be more pronounced on the propagation speed and energy flux of short waves than those of long waves. It is noted that the short waves play a very active role in wind-wave and wave-wave interactions.

The effects of wind drift on wave propagation have been estimated by several investigators for currents of various vertical distributions. For example, Taylor (1971) has considered the case when the current is uniform within a surface layer and vanishes below this layer, Lilly (1966) has assumed that the

gradient of the wind drift is constant, and Phillips (1973) has adopted a model in which the drift current decays exponentially with increasing depth. Limited experiments (Francis and Dudgeon 1967, Plate and Trawle 1970, Wright and Keller 1971, and Shemdin 1972), have been conducted in laboratory wave tanks to study the effects of wind drifts as well as artificial currents on the celerity of surface waves. The distribution of currents in most cases, however, was not measured by the authors.

The present experiment on effects of wind drift on surface-wave propagation consists of two series, one with wind blowing over mechanically generated waves and the other with wind-generated waves alone. The former series with simple regular waves provided a direct measurement of the influence of wind drift on wave propagation, while the features of this influence on irregular wind waves was explored in the second series. During both series, the modification of the phase velocity of the waves, along with the current profiles, were measured, and found to follow qualitatively the trend of Phillips' estimation. The results show quantitatively the selective influence of wind drifts with greater effects on the propagation of shorter waves.

2. EXPERIMENT

2.1 Wave Tank and General Arrangement

The experiments were conducted in a wave tank, 23-m long with a 1.5 by 1.55-m cross section. Mounted at the upstream end

of the tank is an axial flow fan, driven by a variable speed motor; a permeable-type wave absorber is installed at the downstream end. The maximum obtainable wind velocity within a 0.35-m high air passage above 1.2-m deep water is 14 m/sec. The tank is also equipped with a mechanical wave generator, a flap with its lower edge hinged at the bottom of the tank and with its upper edge oscillated at any desired frequency and amplitude by a motor. The fan and the mechanical wave generator can be operated either separately or simultaneously. A detailed description of the tank has been given elsewhere (Wu 1968).

2.2 Measurements of Waves on Currents

The measurements of the phase velocities of waves on currents consisted of two series. In the first series, the wind was blowing over mechanically generated surface waves. The wind velocity was so chosen that the waves remained simple and of progressive type, with a single frequency. For the second series, the waves were generated solely by the wind. A general observation showed that rhombic wave cells were excited before the wind boundary layer became fully rough ($U < 3$ m/sec, where U is the free-stream velocity of the wind); the waves forming the cells were short gravity waves. As the wind velocity increased, the propagation of waves became more and more along the direction of the wind. Parasitic capillaries were formed in front of the gravity-wave crests immediately following the transition of the wind boundary layer from smooth to rough. The water surface was generally smooth

elsewhere. As the wind velocity increased beyond 9 m/sec, ripples were seen covering evenly the water surface, and breaking occurred along the wave crests which spanned transversely across the tank.

The wave height was measured by a conductivity probe, made of a partially submerged platinum wire (0.12 mm in diameter) acting as one electrode and a fully submerged aluminum plate as the other. The output of the probe depends upon the electric current flowing between the two electrodes, which in turn is proportional to the submergence of the wire. Two probes were used in both series of experiments. For the first series, the upwind probe was fixed and the downwind probe was supported on a sliding scale. As illustrated in Figure 1a, the distance between the two probes was adjusted so as to make the two wave signals, monitored on the scope, oscillating approximately in phase. This distance is therefore the estimated wavelength (λ), which was further corrected for any mismatches (Δt) between the recorded signals from two probes; see Figure 1a, where T is the wave period. During the second series of experiments with wind waves of variable lengths, it was not possible to use the previous technique. For this case, the two probes were fixed and separated longitudinally by a distance of 5.1 cm. This distance was tested to be close enough to register nearly identical wave profiles for the same progressive wave, and also to be far enough to avoid any electronic interference between probes. The period of each wave and the time elapsed for the same wave traveling from the first to the

second probe were read directly from the records; the phase speed and the wavelength were subsequently determined from these readings and the distance between two probes; see Figure 1b.

Surface floats were used in the present experiment to determine the current at the air-water interface. The floats were made of plastic discs, 1 cm in diameter and 0.4 m thick. The velocity indicated by the float consists of both wave-induced Stokes mass transport and wind-induced shear current; these two components were later separated.

3. ANALYTICAL CONSIDERATION

The celerity of surface waves of infinitesimal amplitudes may be expressed as (Lamb 1932),

$$C_o^2 = \frac{g}{k} \tanh (kD) + \frac{k\sigma}{\rho} , \qquad k = \frac{2\pi}{\lambda} \qquad [1]$$

wherein C_o is the wave celerity, g is the gravitational acceleration, k is the wave number, D is the water depth, σ is the surface tension, ρ is the density of water, and λ, as defined in Figure 1, is the wavelength. The surface-tension effect on wave propagation diminishes rapidly as the wavelength increases. For gravity waves in deep water, we have

$$C_o = \sqrt{g/k} \qquad \text{with} \qquad kD >> 1 . \qquad [2]$$

As mentioned earlier, the influence of wind-induced drift on the propagation of surface waves has been studied by Taylor (1971), Lilly (1966) and Phillips (1973). For the vertical distribution of the current decreasing with the increasing depth, Lilly assumed a simple linear variation and Phillips adopted a more realistic exponential decay. The latter distribution can be expressed as

$$v(z) = Ve^{-\gamma z} = Ve^{-z/z_0} \quad , \quad z_0 = 1/\gamma \qquad [3]$$

where v is the drift current at a depth z below the surface, V is the surface drift current, and z_0 is a length characterizing the decay of current with depth.

The following implicit equation was obtained by Phillips for determining the phase velocity of deep-water waves on drift currents

$$\frac{g}{k} = V^2(\beta-1)^2 \left[1 + \frac{\gamma f'(1)}{k f(1)}\right] + V^2 \frac{\gamma}{k} (\beta-1) \qquad [4]$$

where $f(1)$ is a power series $f(y)$ with $y = 1$

$$f(y) = 1 - \frac{1}{\alpha\beta} y + \frac{(\alpha-1)}{2\beta^2\alpha(\alpha+1)} y^2 - \frac{(\alpha-1)(2\alpha+1)}{2 \cdot 3\, \beta^3\alpha(\alpha+1)(\alpha+2)} y^3$$

$$- \frac{(\alpha-1)(2\alpha+1)(3\alpha+5)}{2\cdot 3\cdot 4\, \beta^4\alpha(\alpha+1)(\alpha+2)(\alpha+3)} y^4 \cdots\cdots \qquad [5]$$

and y, α, and β are defined as

$$y = e^{-\gamma z} \ , \ \alpha = 1 + 2k/\gamma \ , \ \beta = C_m/V \qquad [6]$$

in which C_m is the phase velocity of waves on wind-drift currents.

Numerical results of Equation [4] showing the influence of wind drift on wave propagation are plotted in Figure 2. Calculations, performed for various values of λ/z_o, illustrate that a current varying slowly with depth has a greater effect on wave propagation than one which varies more rapidly with depth. In other words, for the same current, the influence on the propagation is more pronounced for shorter waves. For a given wave, the influence is more pronounced for a more deeply extended current. The rather strong convective effect on waves produced by even a shallow current is seen in Figure 2, as $(C_m - C_o)/V$ is nearly unity for $\lambda/z_o = 1$.

It was also suggested by Phillips that while the detailed results for various current distributions (two-layer model, linear variation and exponential decaying) are different, when the results are expressed in terms of the ratio between the wavelength and a characteristics length of the current distribution, the various results would be similar.

4. WAVE AND CURRENT CONDITIONS

4.1 Phase Velocity and Stokes Transport of Surface Waves

The phase velocity and Stokes transport of stable surface waves generated mechanically in the present tank are shown in Figures 3a, b. For the wave propagation, the phase velocity for infinitesimal waves in deep water, [2] with added surface-tension term, is also shown in Figure 3a, and is seen to represent closely the measured values. The surface-tension term shown in [1] contributes about 5 percent to the calculated wave celerity at the high-frequency end and about 2 percent at the low-frequency end shown in Figure 3a.

As for the surface drift, the data for long (low-frequency) waves also follow closely the value indicated by the Stokes transport, W,

$$W = C_o \, (\pi H/\lambda)^2 \qquad [7]$$

in which H is the wave height. However, as the wave frequency increases, the ratio between the measured and the calculated values increases with increasing wave frequency. A continuous line is drawn in Figure 3b to show these trends. It is noted that there is no systematic variation of this ratio with the wave steepness, H/λ, which is less than 0.1 in all cases. The only other set of experimental results available on Stokes transport of regular surface waves is that reported by Russel and Osorio (1957). The mass transport at the surface obtained by them was in

good agreement with [7]. However, their experiment included only long waves with the maximum wave frequency of 11.5 rad/sec, about where the present results start to show an increase of the measured value over the prediction. More studies are required to understand, and to provide a quantitative expression of, the surface mass transport of short waves; our only purpose here is to separate the wave-induced and wind-induced components of the surface drift.

4.2 Exponential Decay of Wind Drift

The vertical distribution of the wind-induced drift current in the present tank has been reported elsewhere (Wu 1973). The current close to the water surface tended to vary linearly with the depth, whereas the current near but not too close to the water surface tended to vary logarithmically. The data within a shallow layer, covering the entire linear-variation region and extending into the logarithmic-variation region, are replotted in Figure 4a; an exponential decay curve was forced to fit the data and is seen as the solid line. It is noted that the expression [7] and the results described in the previous section are the surface mass transport for small-amplitude waves and may not be applicable to short steep wind waves. In view of this uncertainty, no attempt is made in this case to separate the mass transport from the wind drift.

The length characterizing the vertical decay of the current, or the depth at which the current is reduced to e^{-1} of the surface drift, is shown in Figure 4b. A drastic change is seen at U = 2 m/sec, which probably signifies the transition of the current boundary layer from laminar to turbulent. When compared with the dominant wavelength, the length characterizing the exponential current decay is seen in Figure 4c to decrease first rapidly and then more gradually with the increasing wind velocity, and appears to approach a value of about 1/30 at high wind velocities. More will be discussed later regarding the increase of the length of dominant waves and the thickness of the current boundary layer.

5. INFLUENCE OF WIND DRIFT ON WAVE PROPAGATION

5.1 Influence on Simple Progressive Waves

During this series of experiments, wind with velocity less than 2.5 m/sec was blowing over mechanically generated surface waves. The wind velocity was chosen so as to provide appreciable wind drift and at the same time to maintain a stable wave profile. The phase velocity and the drift current obtained under wind were deducted by the respective value of the pre-existing waves under no wind. The phase velocities and the surface transports of the pre-existing waves are those shown in Figure 3. The increase in the phase velocity is considered to be due to the effect of wind drifts, and the increase in the drift current is considered to be the wind-induced drift current.

The ratio between the increase in phase velocity and the wind drift is plotted versus the radial wave frequency ω in Figure 5. No detailed measurements of the drift profiles were made in this case with wind blowing over mechanically generated surface waves. However, since the wind velocity for this series of experiments is within the range between 1 and 2.5 m/sec, the waves are generally very small in amplitude. The drift profile shown in Figure 4a is therefore applicable here. The characteristic lengths for the current decay, shown in Figure 4b, appear to be divided into a rapid and a gradual varying regions, with respect to the wind velocity, separated at $U = 1.5$ m/sec and $z_o = 0.75$ cm. Taking this division, two different symbols are used in Figure 5 to identify the data.

Despite the considerable scatter, two definite trends are illustrated by the data. The influence of the wind drift on the wave propagation is seen to be greater for shorter waves with higher frequencies. The more shallowly distributed current with smaller z_o has less influence.

Assuming various characteristic lengths for the current decay, $z_o = 0.5$, 1, 2, and 3 cm, the increase of phase velocity due to wind drift were calculated from [4] and are drawn in Figure 5. The trend of the experimental results is seen to be in general qualitative agreement with, but greater than, the calculated values.

5.2 Influence on Wind Waves

During the second series, the dominant waves excited at each wind velocity were measured simultaneously by two probes. As discussed earlier and illustrated in Figure 1b, the celerity and the length of dominent waves can be determined from the wave period, the distance between the two probes, and the elapsed time for the same wave to travel from the first to the second probe. It is noted that the lengths of waves in this series of experiments were much shorter than the water depth (1.3 m) and belonged to the category of deep-water waves.

For each wind velocity, the ratio of the difference between the calculated and the measured celerities and the wind-induced surface drift, $(C_m - C_o)/V$, is plotted versus the radial wave frequency in Figure 6. The wind waves excited at low wind velocities in the present tank generally propagate at a small angle to the wind direction; this angle decreases as the wind velocity increases, and is negligible at high wind velocities, that is for $U > 9$ m/sec. The correction for such effects involves the cosine of this angle, which is no greater than 20° even at the lowest wind velocity. Since the cosine of such a small angle is insignificantly different from unity, the direction of wave propagation was not measured in the present experiment.

The data shown in Figure 6 exhibit considerable scatter. Such scatter is to be expected, since wind waves have components of various lengths and move at various speeds, while in the present

experiment we ignored this basic structure and chose only to measure the dominant waves. Furthermore, the drift current, which influences the wave propagation, is neither steady temporally nor uniform longitudinally. However, the trend of the data shown in Figure 6 indicates clearly once again that for the same wind velocity, the effects of drift currents diminish as the wavelength (inversely proportional to the wave frequency) increases. Taking the surface drift current from an earlier study (Wu 1968) and the characteristic length shown in Figure 4, the predicted influence was calculated from [4] and is shown as solid lines in Figure 6. The distribution of the wind drift immediate to the water surface could not be measured at high wind velocities in the present tank, as the entraining motion associated with wave breaking tended to sink the submerged floats (Wu 1973). Thus the characteristic length for the current decay at high wind velocities was obtained, by extrapolation, from the fitted curve shown in Figure 4c.

The calculated values are seen in Figure 6 to be in qualitative agreement with the measured results. In view of the several approximations involved, a more detailed comparison between calculations and measurements may not be merited. One interesting feature is that in comparison with measurements, the calculations appear to show less variation with the wind velocity, or equivalently, with the wind drift and its distribution.

5.3 Probable Influence on Ocean Waves

As shown in Figure 2 and discussed in an earlier section, the influence of the wind drift on the propagation of surface waves varies significantly with the depth to which the current penetrates, expressed in terms of z_o/λ. This depth is related to the development of the current boundary layer which, like the waves, grows with the fetch. The current boundary layer is generally turbulent, and its thickness δ may be estimated from (Schlichting 1968)

$$\delta/L = 0.377/\mathbb{R}^{1/5} \text{ , } \mathbb{R} = VL/\nu \qquad [8]$$

in which L is the fetch, $\mathbb{R}$ is the fetch Reynolds number, and ν is the kinematic viscosity of water. Wave data obtained at various fetches were compiled by Weigel (1962) and faired by Wu (1969) with the following result:

$$C/U = 0.0502\ (gL/U^2)^{0.3} \qquad [9]$$

where C is the phase velocity of the dominant waves. For deep-water waves, the length of the dominant waves can be obtained from [9] and compared with the boundary-layer thickness in Figure 7a. The boundary-layer thickness is seen to increase with the fetch faster than the length of the dominant waves; consequently, the influence of the wind drift on the wave celerity, expressed in terms of the surface drift, becomes more pronounced at longer fetches.

As shown in Figure 3, for the same value of λ/z_o, the ratio $\Delta C/V$ varies inappreciably with V/C_o; therefore, the ratio $\Delta C/C_o$ should vary almost linearly with V/C_o. In other words, the percentage of the change of the wave celerity due to wind drift varies almost inversely with the unperturbed celerity. Under various wind velocities, the phase velocities of dominant waves for different fetches can be calculated from [9] and are plotted in Figure 7b.

In summary, as the fetch increases, the current boundary layer becomes relatively thicker with respect to the increase of the dominant wavelength, and in the meantime, the phase velocity of the dominant waves also increases. On the other hand, the ratio between the wind drift and the wind velocity decreases gradually with the increasing fetch (Wu 1973). Taken together, the above dependance imply that the influence of the wind on the celerity of dominant waves becomes less important as the fetch increases. However, since the ocean waves consist of waves of various lengths propagating at various speeds, the influence of wind drift on the propagation of wave components having lengths comparable to those presented in the present experiments should be more pronounced.

REFERENCES

Francis, J.R.D. and Dugeon, C. R., 1967, "An Experimental Study of Wind Generated Waves on a Water Current," Quart. J. Roy. Meteorol. Soc., 93, 247-53.

Lamb, H., 1932, "Hydrodynamics," 6th Edition, Dover Publications, New York.

Lilly, D. K., 1966, "On the Speed of Surface Gravity Waves Propagating on a Moving Fluid," J. Fluid Mech., 26, 683-87.

Phillips, O. M., 1973, "The Influences of Wind Drift and Capillarity on Blockage," HYDRONAUTICS, Incorporated Technical Report 7211-1.

Plate, E. and Trawle, M., 1970, "A Note on the Celerity of Wind Waves on a Water Current," J. Geophys. Res., 75, 3537-44.

Russel, R.C.H., and Osorio, J.D.C., 1957, "An Experimental Investigation of Drift Profiles in a Closed Channel," Proc. Sixth Conf. Coastal Eng., University of California, Berkeley.

Shemdin, O. M., 1972, "Wind-Generated Current and Phase Speed of Wind Waves," J. Phys. Ocean ., 2, 411-19.

Taylor, G. I., 1971, "Scientific Papers, Vol. 4," p. 255, Cambridge University Press.

Weigel, R. L., 1964, "Oceanographical Engineering," Prentice-Hall, Englewood Cliffs.

Wright, J. W. and Keller, W. C., 1971, "Doppler Spectra in Microwave Scattering from Wind Waves," Phys. Fluids, 14, 466-74.

Wu, Jin, 1968, "Laboratory Studies of Wind-Wave Interactions," J. Fluid Mech., 34, 91-112.

Wu, Jin, 1973, "Wind-Induced Drift Currents," HYDRONAUTICS, Incorporated Technical Report 7303-1.

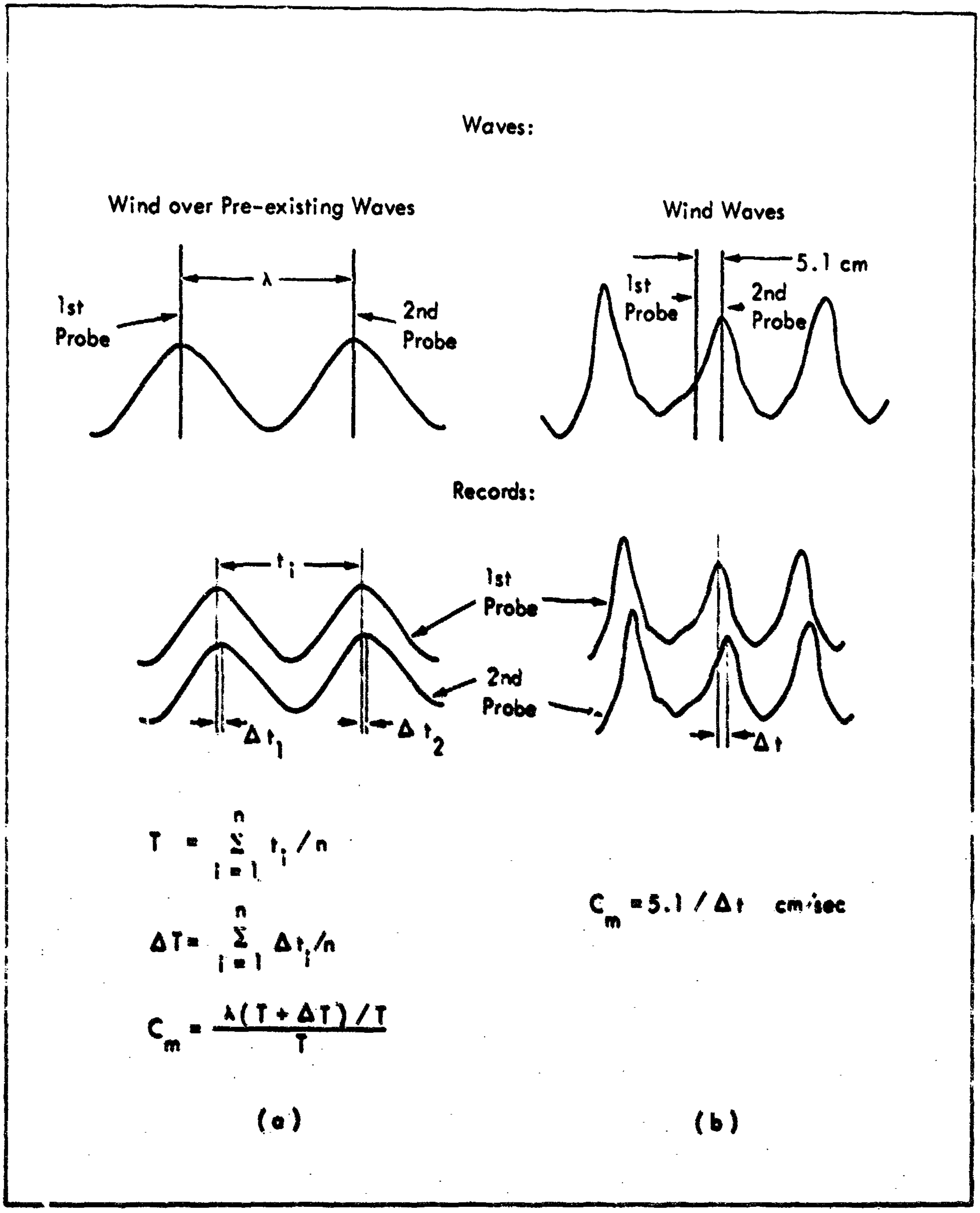

FIGURE 1 - TWO ARRANGEMENTS FOR MEASUREMENTS OF PHASE VELOCITIES

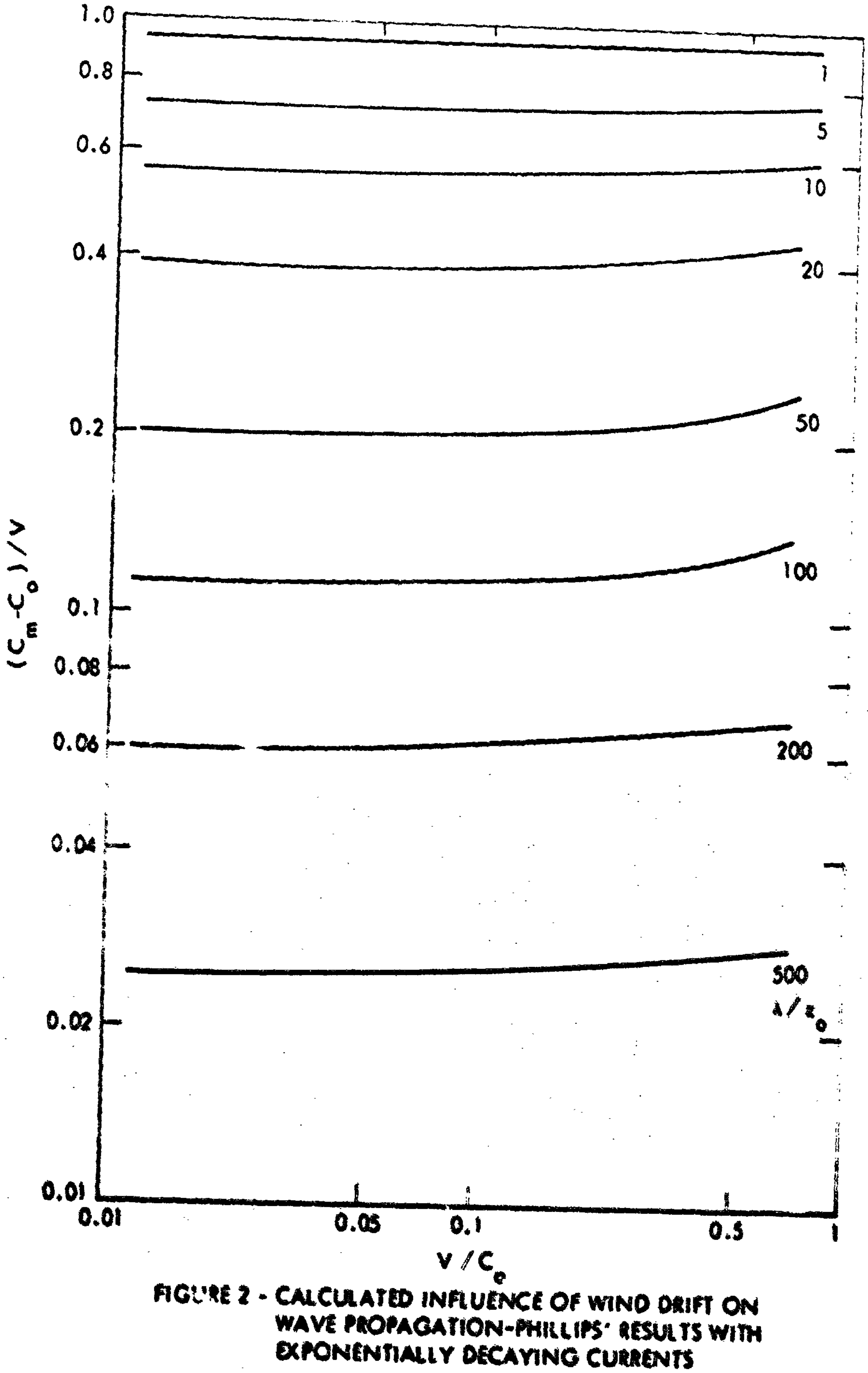

FIGURE 2 - CALCULATED INFLUENCE OF WIND DRIFT ON WAVE PROPAGATION-PHILLIPS' RESULTS WITH EXPONENTIALLY DECAYING CURRENTS

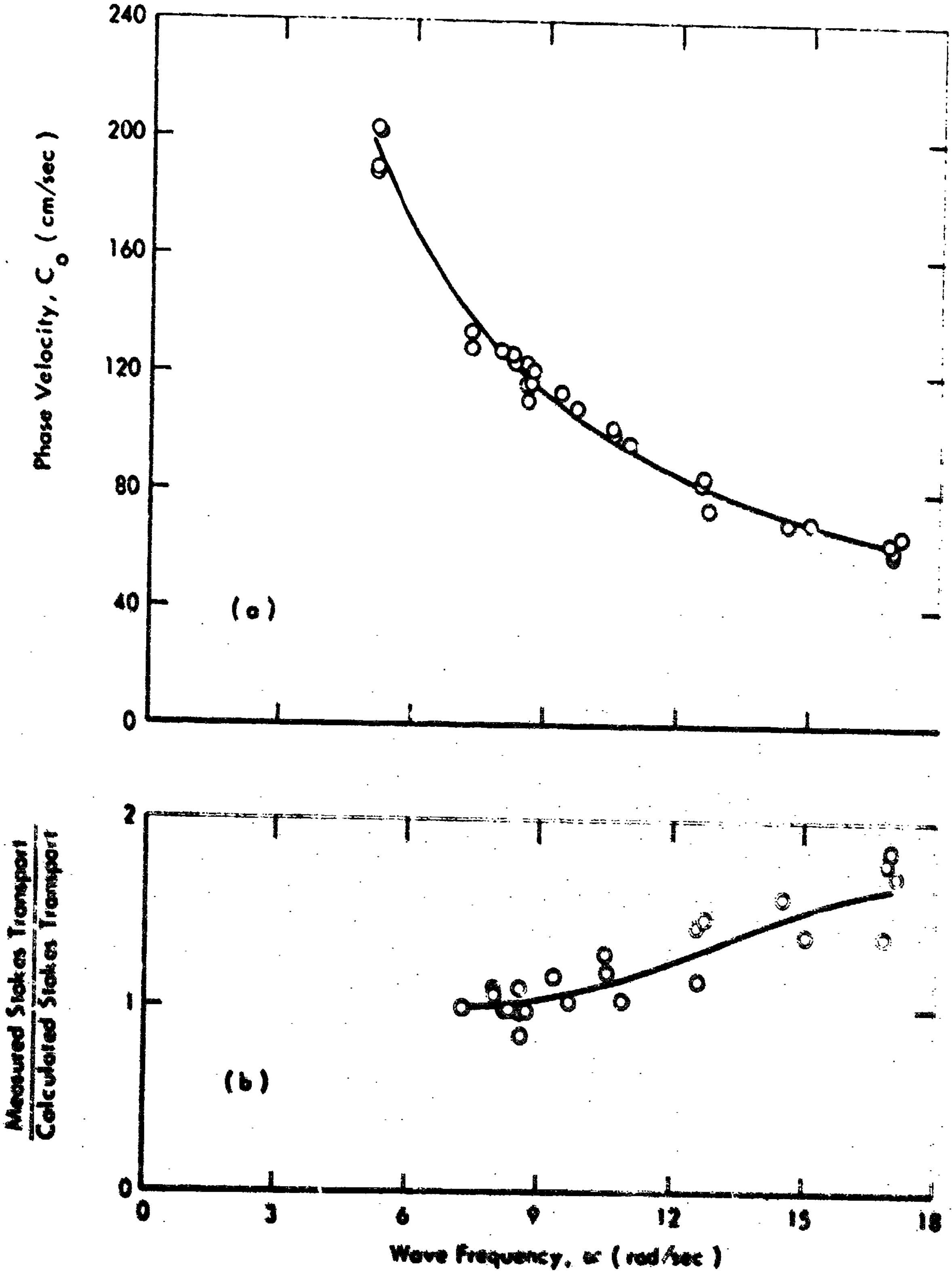

FIGURE 3 - PHASE VELOCITIES AND STOKES TRANSPORTS OF SURFACE WAVES

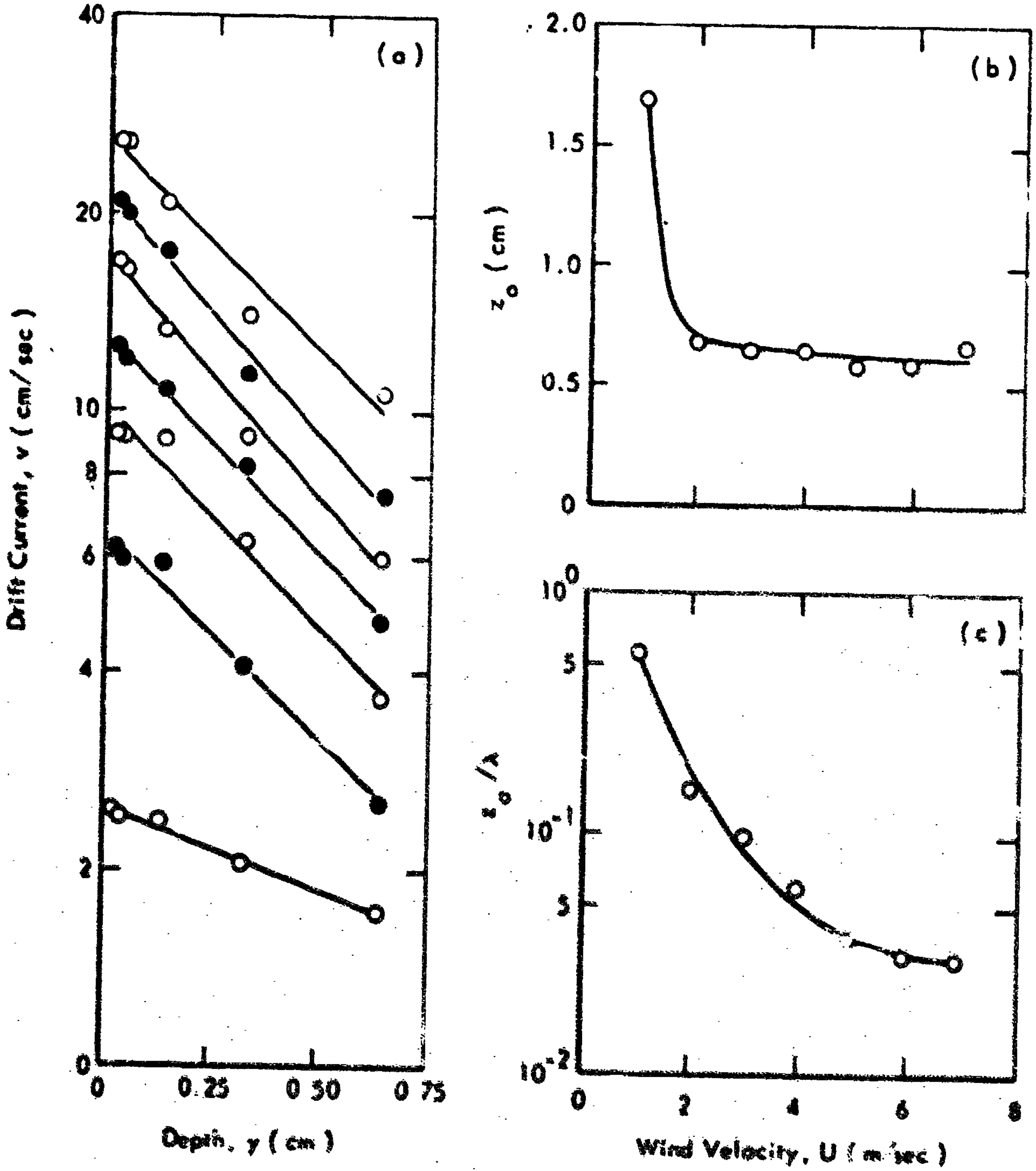

FIGURE 4 - DISTRIBUTION OF WIND DRIFT IMMEDIATE TO WATER SURFACE

The current distributions shown in (a) from bottom to top were obtained in the order of increasing wind velocities. The characteristic lengths shown in (b) were deduced from (a) at these velocities.

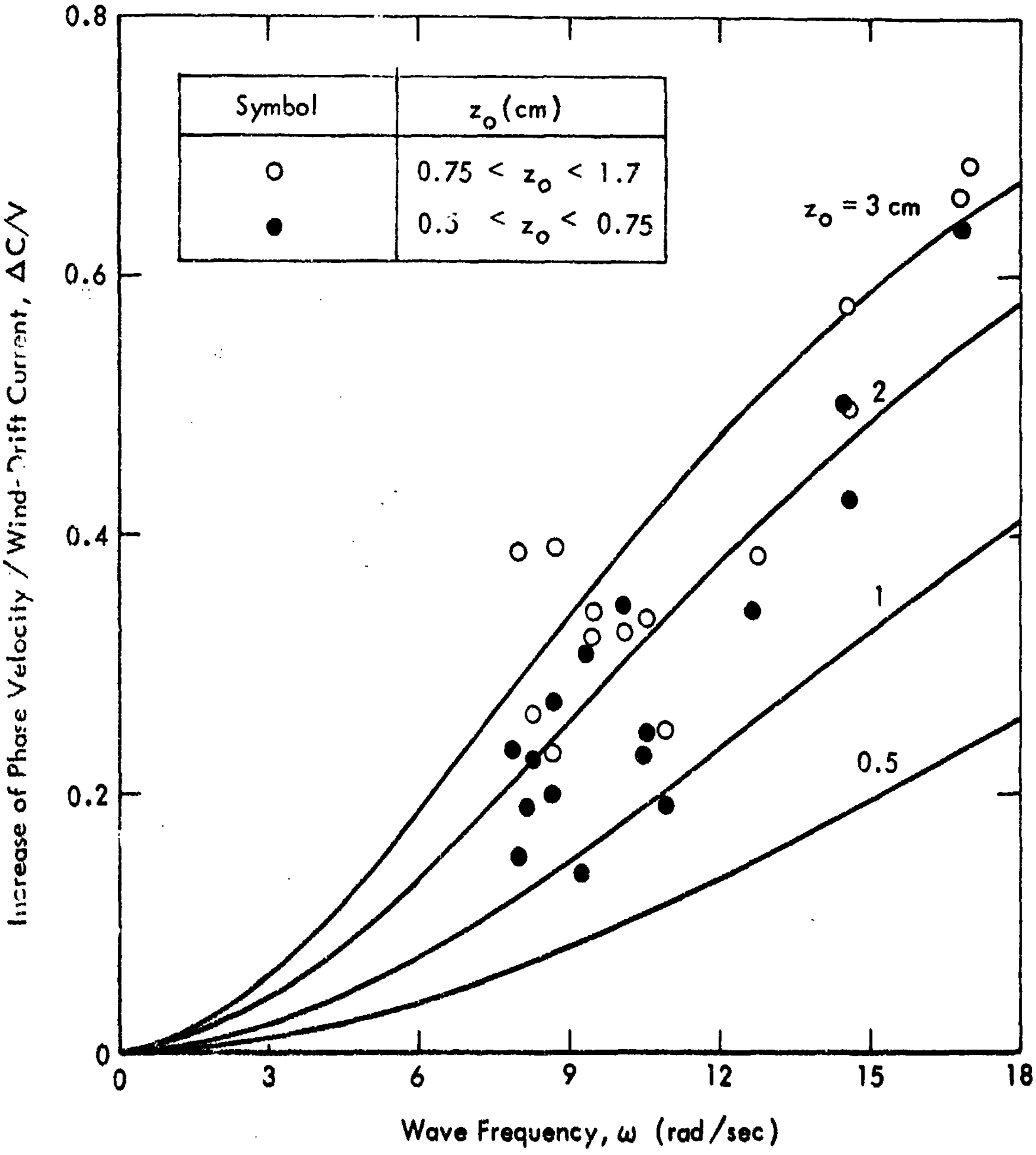

FIGURE 5 - MEASURED AND CALCULATED INFLUENCES OF WIND DRIFT ON PHASE VELOCITY OF SURFACE WAVES

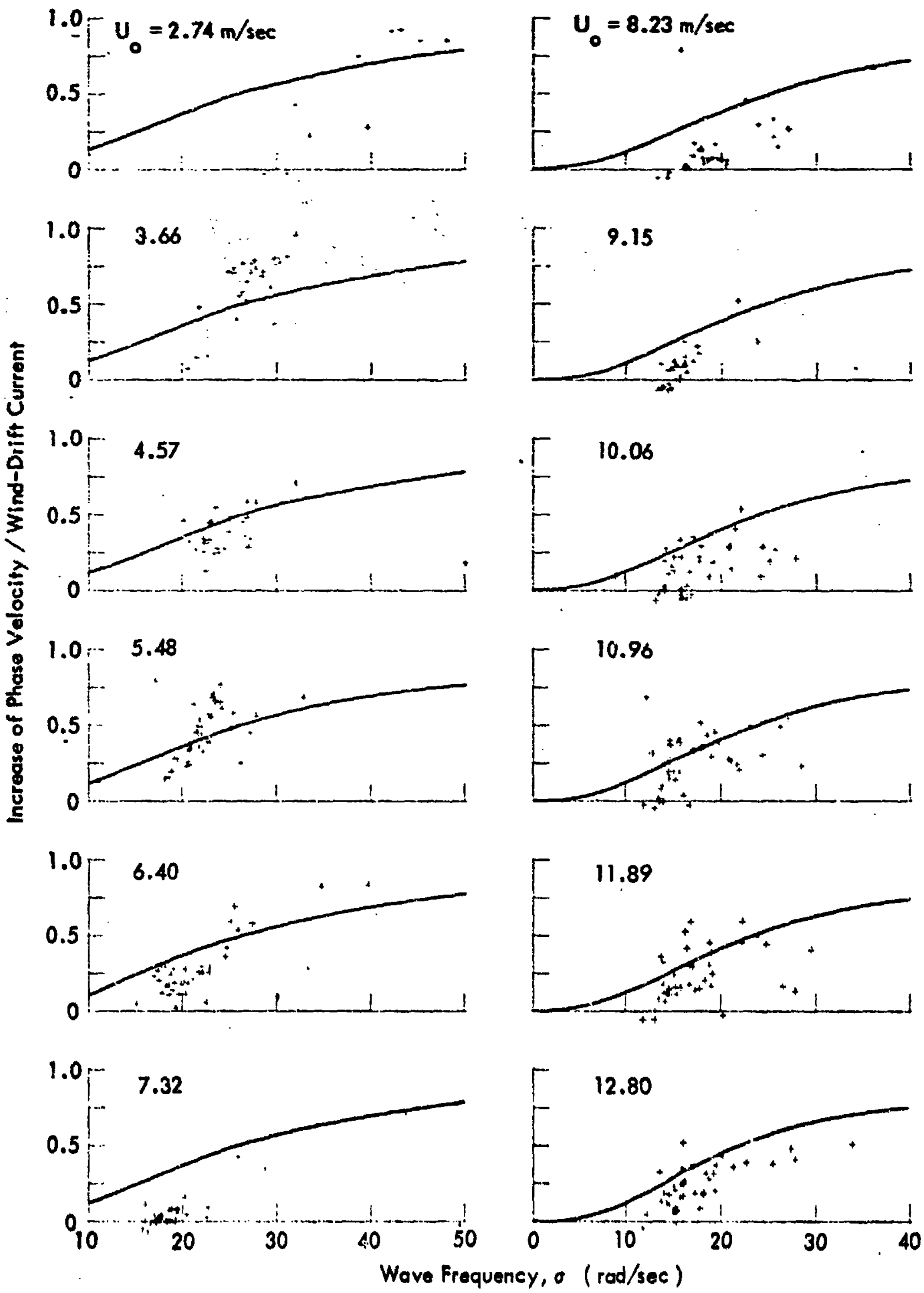

FIGURE 6 - INFLUENCE OF WIND DRIFT ON PHASE VELOCITY OF WIND WAVES

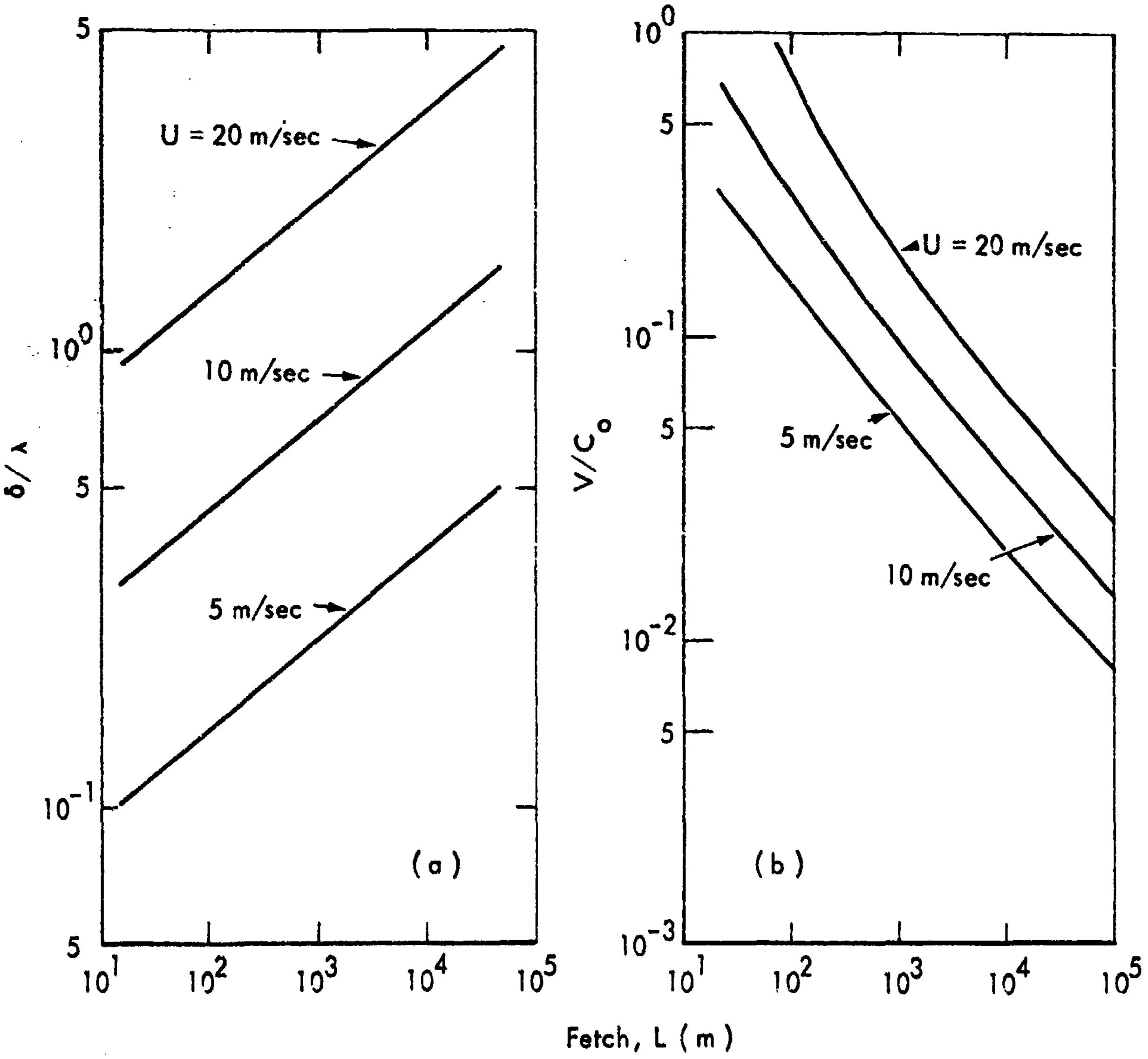

FIGURE 7 - COMPARISON BETWEEN WIND-DRIFT AND SURFACE WAVE CHARACTERISTICS UNDER VARIOUS WIND VELOCITIES AND AT DIFFERENT FETCHES.